

1 NANO-SIZE GAS SENSOR SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

5 This application claims the benefit of U.S. Provisional
Application No. 60/246,988.

FIELD OF INVENTION

10 This invention is in the field of nano-size gas sensors that
employ photons to interact with the sensing material in some way.
This nano-technology includes the use of photon absorption,
refraction, reflection and optical ~~evanescent~~ evanescence. The
invention incorporates a sensing media, which comprises a chemical
complex outside and/or immediately adjacent to a photon source ~~and~~
~~or~~ and/or waveguide, e.g., a chemical media that changes its optical
15 properties in response to gases and vapors. There are a number of
applications[7] where nano-scale ~~sensor by~~ sensors employ evanescent
coupling from a waveguide to a porous coating containing a chemical
that reacts with a gas or vapor to cause a change in the photon
signal ~~though~~ through the waveguide. This evanescent method can
20 provide very fast CO response to even low levels of target ~~targets~~
gases and is also a valuable [a] method to ~~detected~~ detect a variety
of gases that can react with a thin layer coated onto a waveguide.
In addition, the nano-scale sensors can be used to ~~as that~~ employ a
multi-pass photon chamber or an optical switch that employs a change
25 to the index of refraction of the sensor to move ~~photon~~ photons from
one waveguide to another. There are other nano-technology sensing
methods that can be used to make gas sensor; however, this ~~patent~~
invention deals with the optical method in the broad sense that
photons are used. These optical methods include some interaction of
30 the photons with matter, a photon emitter, a photon detector and a
miniature sensor system.

BACKGROUND OF THE INVENTION

35 In recent [~~year~~] years, a number of MEMS and MOEMS devices
have been developed. These miniature machines and electro-optical

1 devices may be fabricated using the photolithography techniques
developed for silicon devices, such as turbines, switches, sensors
and actuators. The micro-machining industry is in its infancy as was
the silicon integrated circuit (IC) device industry [~~was~~] 40 years
5 ago. As design tools made possible the development of the IC
industry, design tools are beginning to give today's researchers the
opportunity to design new components combining the physical world
needs of sensing and actuators with the rapidly growing capabilities
of information technology.

10 In 1994, Quantum Group proposed to DOE STTR (94-1) the
"Evanescent Detection of Gases". This document was proprietary and
not a public disclosure, but turned [~~turn~~] out to be a prescription
for a new and better evanescent sensing method, which has been
recently reduced to practice. The proposed evanescent system was
15 designed to detect gases such as CO, H₂, D₂, T₂, H₂S, NO_x, UF₆, F₂,
PuF₆, CI₂ and ammonia.

One application of these proposed miniature evanescent sensors
is to detect clandestine nuclear or chemical weapon facilities.
Other applications are to monitor plumes from existing facilities,
20 measure gases to control engines, fuel cells and other processes,
environmental monitoring, safety and detect terrorist activities.

This proposal extends the well-known evanescent fiber optic
sensor for detection of various ions in the liquid and gaseous
phases (Harrick 1987; Mirabella 1985, Paul 1987; Simhony 1988 and
25 Ruddy et al 1990; S. Shilov et al Proceedings of SPIE Vol. 3918
(2000) and Holmquist 1993). Bell and Firestone (1986) and others
(1985) have stated that many fiber optic systems can convey photon
signals with nearly zero attenuation (losses).

Airborne gases and vapors such as hydrocarbons, NO_x, hydrogen,
30 carbon monoxide, nerve and mustard agents as well as other gaseous
and vapors are generally detected by various instruments in the lab
and field. Until very recently, this equipment was very large and
[~~the~~] expensive. The US government and many companies have embarked
on methods to increase the speed of detection and to reduce the size
35 of the detectors. The advent of MEMS and MOEMS has made possible the

1 miniaturization of various sensors. In addition, ~~chemioptical~~
2 chemioptical methods developed by Quantum Group in the 1980s [~~lead~~]
3 have led to commercialization of very low powered biomimetic sensors
4 in the 1990s.

5 Goldstein et al described examples of a CO sensing using
6 biomimetic sensors, e.g., US Patent No. 5,063,164, US Patent
7 No. 5,618,493, and patent application No. 09/487,512 filed
8 Jan. 19, 2000, the contents of which are incorporated by reference.
9 These biomimetic sensors mimic the human response to CO. This
10 chemistry was an improvement of an earlier invention by Shuler and
11 Schrauzer, i.e., US Patent 4,043,934. The Shuler and Schrauzer
12 Patent also teaches the use of a chemistry with high copper ion
13 concentration that ~~convert~~ converts CO to carbon dioxide even at
14 room temperature, but has limited life and operates over a narrow
15 range of relative humidity.

16 US Patent 5,063,[-]164 teaches that in the presence of the
17 target gas the danger from [~~a~~] hazardous exposures may be determined
18 by monitoring the sensor with a photon source, i.e., passing photons
19 of a specific spectral region ~~though~~ through the sensor and ~~monitor~~
20 monitoring the intensity of the photon beam or [~~use~~] using a pulsed
21 photon source to conserve power with a simple photon detector such
22 as a photodiode. There are a number of other target gas sensors that
23 have been disclosed in ~~the following~~ US Patents, e.g.,
24 Nos. 4,043,934, 5,346,671, 5,405,583, 5,618,493 and 5,302,350, which
25 can detect a target gas such as CO by ~~monitor~~ monitoring the optical
26 properties of the sensor.

27 Goldstein described several CO detector systems which
28 incorporate these type of optical changing sensors, such as the
29 biomimetic sensor as discussed above, such as US Patent Nos.
30 5,280,273, and 5,793,295 ~~and others.~~ Others such as by Marnie et al
31 ~~disclose~~ disclosed a low cost circuit (Apparatus) with software and
32 method for detecting CO in US Patent Nos. 5,573,953 and 5,624,848.
33 Goldstein et al further disclosed a digital and rapid regenerating
34 means in co-pending patent applications 08/026,34 and 60/076,822
35 herein incorporated by reference. The SIR technology is described in

1 a copending application 60/051,038 filed June 27, 1998, which [~~use~~]
uses a sensor that responds to CO by a change in its optical
properties, for example, as described in ~~patents~~ US Patent No.
5,063,164 and the improvement patents mentioned ~~above~~ herein in
5 example 1 and co-pending applications.

The gas detector systems include housings that ~~containing~~
contain one or more photon sources that ~~emits~~ emit photons in at
least a region of the electromagnetic spectrum[~~-The~~], a sensor that
absorbs photons proportional to the CO exposure[~~-and~~], a
10 photodetector sensitive in the corresponding active region of the
spectra, a circuit designed to measure the response[~~-and~~], a noise
maker or other signal means which are actuated by the circuit and an
enclosure. The housing (enclosure) has at least one opening to
permit the sound to escape and the CO or other gas to enter. The
15 detector also contains a sensor that may be permanent or may be
configured with a battery for convenient replacement or may be
mounted within the housing designed for easy replacement and with or
without a convenient battery replacement means. Several systems were
disclosed in US Pat. No. 5,793,295 by Goldstein issued in August 11,
20 1998 and is hereby incorporated by reference.

In addition, some preferred embodiments of this invention are
portable and can be placed on the vehicles visor or other locations
(e.g., pocket, belt, dash) while driving[~~-however~~]. However, the
portable unit is easily removed for use in other location outside
25 the vehicle such as [a] for CO protection in the workplace by
workers and/or by contractors, fire person, utility or other
serviceperson, etc., or on forklifts and similar vehicles that do
not have visors. These types of portable products may be operated on
common batteries that can be easily replaced. The sensor system may
30 be replace separately or with the battery. The most accurate
detector system able to respond to less than 30 ppm CO contains
sensor(s) that need to be replace occasionally (1 to 5 years).

Several low cost sensor systems are disclosed in US Patent
Nos. 5,063,164, 5,624,848 (Marnie et al), 5,618,493, (Goldstein et
35 al), 5,280,273 (Goldstein), 5,793,295 (Marnie et at) and higher cost

1 advanced systems are disclosed in co-pending applications serial
number 60/076,822 filed March 4, 1998 and a digital CO detector
PCT/US97/16846 Filed 19 Sept. 97, the contents of which are hereby
incorporated by reference.

5 This sensor(s) comprises at least one self-regenerating
sensing reagent coated onto a substrate, for example, a high surface
area transparent material such as a porous glass. The substrate is
made of a solid state material which is sufficiently transmissive or
reflective to a specific range of photons in the specific wavelength
10 region ~~[to]~~ of interest to permit detection of optical
characteristics of the sensor using an optical source such as a
light emitting diode and a photodiode ~~such as photodiode~~. These
optical components and sensor(s) are controlled by a circuit
designed to measure the output of the photodiode monitoring the
15 sensor which would alert the passengers through some means and
actuate controls as programmed depending on the level of hazard or
condition.

These type of detector can be modified to meet any of the
following standards: UL 2034 recreational vehicle, British Standard
20 Institute (BSI) for United Kingdom and Japanese standards.

This may be accomplished by one of several software - hardware
combinations described in US ~~Patents~~ Pat. Nos. 5,624,848 and
5,573,953, herein incorporated by reference, ~~[to]~~ known as
embodiment 1, and co-pending application using digital methodology
25 described in PCT/US97/1686 is known as embodiment 2. Both
embodiments ~~embodiment~~ 1 and 2 are preferred embodiments, the first
for low cost and the second ~~is preferred~~ for performance features
and accuracy, i.e., the high-end application.

Most of the current portable digital gas detection products
30 with acceptable accuracy on the market are battery operated and use
electrochemical cells for sensors~~[, the]~~. The units that are
accurate are expensive, costing typically \$500 to \$1000, require
frequent calibration~~[,]~~ and frequent sensor and battery
replacements. These electrochemical units can not operate ~~[a]~~ at -40
35 C nor can they live for long periods of time at 70 C. Metal Oxide

1 Semiconductor sensors take very large amounts of power and therefore
cannot be operated for a reasonable time of 2 years on a small 9
volt battery. The MOS sensors ~~senser~~ are subject to interfering
gases and also lose sensitivity when exposed to silicones often used
5 in the automotive industry. Therefore, there is a need for a low-
cost, reliable, low power, accurate, easy to use, and low power
consuming unit to detect various gases, such as CO, rapidly even at
very low levels as required by fuel cell vehicles. There is a need
to incorporate the product into fuel cell vehicles to have a product
10 that can be used to control the reformer with response time of 100
milliseconds.

Furthermore, there is a need for a small CO detector to
protect people. A pocket size model has additional advantages of
operating over a larger range of humidity and temperature,
15 responding faster and providing more accuracy and more stability
than any other technology.

Specifically for the case where the target gas is CO, ~~and~~
the sensor is one or more CO optically responding sensors, such as
described in US Patent ~~number~~ No. 5,063,164. There are improvements
20 in that technology such as those described in the patent mention
above or in copending applications referred to above such as
Application No. 60/051,038 filed as ~~a regular~~ an ordinary patent
application on June 26, 1998 entitled Air Quality ~~chamber~~ Chamber,
herein incorporated by reference. The humidity and air quality
25 system incorporates [a] catalyst formulations sold under the ~~trade~~
~~name~~ trademark SIR(TM). These sensors are more selective and live
much longer than any other sensors on the market.

Acid gases such as sulfur dioxide, sulfur trioxide, oxides of
nitrogen, and similar acid compounds may be removed from the air
30 stream by means ~~a-getter~~ comprising a porous air filter ~~mater~~
material impregnated with acid reacting chemical such as sodium
bicarbonate, sodium carbonate, calcium carbonate and magnesium
hydroxide. In addition, there is a filter section to react with
bases such as citric, tartaric, phosphoric, molybdosilicic and
35 other acids impregnated on silica gel or other suitable substrate. A

1 layer of charcoal may separate the acid from the basic layer[7]. A
useful air purification system may include ~~4 to 5~~ four to five
active ~~layer~~ layers separated by inert material such as a porous
felt.

5 An optically responding sensor for detecting the presence of a
predetermined target gas, such as carbon monoxide ("CO"), is
disclosed in US Patent No. 5,063,164, ~~and~~ the contents of which
are hereby incorporated by reference. The sensor comprises at least
one self-regenerating sensing reagent coated onto a substrate, for
10 example, a high surface area transparent material. The substrate is
made of a solid state material such as silica. The substrate must be
sufficiently transmissive to the wavelength of interest to permit
detection of optical characteristics of the sensor using an
optically coupled light emitting diode and photodiode collectors.

15 Other methods for detecting gas, such as methane, using
evanescent field absorption have been demonstrated using silver
halide fiber (Tanaka et al 1985). The halide fibers are very
expensive therefore Simhony et al developed a short halide fiber in
1986. Numerous other methods for detecting gases have been
20 developed, such as detection of ammonia using a pH indicator coated
in the porous layer (Shahiriari et al. 1988). Saggase et al
demonstrated the feasibility of detecting CO, CO2 and methane using
AW3 and ZrF3. These methods are expensive and relatively
insensitive ~~to~~ from 1 to 10 ppm levels. Therefore, ~~a need exist~~
25 exists for a more sensitive and faster CO sensor. In addition, there
is a need for a sensor that is durable and can operate in fuel cell
reformat streams, under high temperature high humidity condition
and be durable enough to operate for years without maintenance and
calibration. In addition, there is a need for a low cost, easy to
30 manufacture and reproducible CO sensor for fire detection and many
other applications, including the detection of CW agents, explosives
and other materials. Therefore, the present invention is important
to meet all these necessary requirements; no other technology can
meet these requirements.

1 Certain vehicles, such as electric cars powered by fuel cells,
were generally expected to comprise a hydrocarbon reformer to
convert hydrocarbon to hydrogen, carbon dioxide and carbon monoxide.
The CO sensing system may operate off of the main vehicle electric
5 power generated by the fuel cell or other electric generation means
and may also have a battery back up system. ~~One reason that~~
~~increased~~ Increased response speed in the millisecond time frame is
as a result of the need to control reformers for fuel cells and
increase the efficiency of the fuel cell.

10 SUMMARY ~~THE FIELD~~ OF THE INVENTION

The field of the invention relates to gas monitoring using
~~senser~~ sensors that respond to gases or vapors by modifying one or
more optical property of the ~~senser~~ sensors.

15 There are numerous applications for the detection of gases and
vapors. One application is to detect hazardous materials such as
explosives at checkpoint. Another application is to identify the use
of chemical warfare agents. The fuel cell reform requires the
detection of CO accurately and reliably at or below 10 ppm. A
20 reference sensor may be used to increase stability ~~and or~~ and/or to
reduce the need for constant calibration. Control sensors measure
the difference in the photons passing through the reference and the
sensing element. It can compensate for various environmental and
other changes.

25 Example 1 Low power sensing systems. In [~~in~~] a preferred low
cost embodiment of this invention, e.g., incorporating one or more
chemioptical responding sensor(s), a low power consuming sensor
monitoring ~~systems~~ system is used for detecting the presence of a
predetermined target gas, such as carbon monoxide ("CO"). Simply by
30 miniaturizing the sensing system, the sensing speed can be increase
because these types of sensors change optical properties as the gas
diffuses into the pores. These pores are small and ~~therefor~~
therefore it takes time for diffusion to take place. The ~~small~~
smaller the sensor, the less time it takes [~~take~~] to change the
35 entire sensor or some fraction thereof.

1 Example 2 illustrates the use of evanescence to increase the
sensing speed of an optical sensor. The sensing speed is increase
by using the evanescent wave absorption (EFA), because the sensing
layer is thin. In one embodiment of the EFA, there is a porous
5 coating that replaces the cladding in a typical waveguide or optical
fiber. The key part of the EFA sensor is the coating of the porous
cladding. For example, a 125-nm thick coating can be applied to an
optical fiber that is 10 microns to 600nm in diameter. The porous
substrate may be made by reaction of the Tetraethyl Orthosilicate
10 ~~orthosilicate~~ (TEOS) with an organic precursor to form an
organometallic acid with more than 4 carbons but less than 12
carbons. The reaction is done in a dry box similar to the method
for making rare earth metal oxide ceramic precursor composition as
described in US Patent No. 5,662,737, ~~and is~~ herein incorporated by
15 reference.

In this Example 2 case, one may mix silicon alkoxide with a
complexing agent to yield a mixture of complexing agent/alkoxide of
silicon. The mixture is then hydrolyzed and the precursor
composition is isolated and is stable in air. The solubility of the
precursor can be tailored to dissolve in various ~~solvent~~ solvents
20 and be controlling the structure and functional groups. The at
least partial dissolution in a solvent creates pre-ceramic liquid
that can be used to coat the waveguide. Pore size can be controlled
by the amount of solvent and pore agent used. The pore agent can be
25 a polymer of a sub-micron insoluble material or a combination of the
above. The pore agent may preferably consist of a material that is
interconnected such that when ~~we burn it~~ it is burned out the pore
structure is uniform and interconnected. A mixture is of
cyclodextrins (CDs) and polymers with functional groups that
30 ~~self-assemble~~ self-assemble with the CDs. In some cases, the
organic complexing agent may act as the pore agent by itself or with
another additive. The coating may be applied by dip coating,
spraying or other similar method.

The fiber is placed in a chamber with an optical emitter and
35 sensor. The photons are placed into the waveguide at one end and

1 read at the other. The EFA is measure at time zero and at various
 exposure of a target gas such as CO. The coiling of the fiber
 reduces the size of the chamber and increases the sensitivity of the
 sensing system by increasing the evanescent wave outside the core
 5 fiber into the outer cladding ~~elassing~~.

For the case where the target gas is CO, ~~[I(n)]~~ a circuit is
 designed to measure the EFA output of the photodiode and/or its
 rate of change, dI/dt . Under certain condition, the derivative is
 proportional to the carbon monoxide (CO) concentration,

$$[CO] = k_1 \{dI/dt\}, \text{ at other times}$$

$$[CO] = k_2 \{I(n)\}$$

when ~~[when]~~ dI/dt is very near zero

~~[and]~~ And, when dI/dt is not linear such that the second derivative
 is not very near zero, than a weighted average is calculated, and

15 the constants k_3 and k_4 represent the proportion of each component on
 the weighted average which may be determine empirically. After the
 constants have been determined for each type of sensor, then the CO
 concentration can be approximated by the following equation

$$[CO] = c\{k_3 [dI/dt] + k_4 [I(n)]\}$$

The approximation can be employed easily and can limit the cost of
 the digital alarm or detector.

In the case where the gas to be measured is a fuel cell
 25 reformat stream, the CO in the stream ~~react~~ reacts with one sensor
 in the linear range. There are two sensors as described in an
 earlier US patent application 09/487,512 filed 1-19-00. One
 embodiment of the invention comprises a control system, which
~~consist~~ consists of two sensors and a valve system to allow the

30 control of air and reformat alternately, such that one sensor is
 always measuring the CO and perhaps the information can be used for
 controlling other systems. This embodiment is referred to as K CO
 Detection system hereafter. The control sensor measures CO in the
 hydrogen stream effectively and at least one sensor is being

35 regenerated by the air stream. The two or more sensors are monitored

1 photometrically, one in the hydrogen stream and at least one in the
air.

5 In the ~~The~~ use of porous silica coatings on a core optical
fiber and then coating or self-assembling a gas sensing material on
the porous surface, there ~~[—There]~~ is a well-known alkoxide coating
method that was developed by Jeff Brinker at Sandia, which was first
tried; however, the coating pore structure was only about 1 to 3 nm
in diameter. This process is good for some sensor material. The CO
sensor requires a pore size of 20 to 25 nm (200 to 250 Angstroms).
10 This pore structure, [is] ~~[is]~~ disclosed in a previous patent for a CO
sensor, US Patent No. 5,618,493 issued August 1997, ~~which~~ exceeds 15
nm or 150 Angstroms. If the average pore diameter is larger than
350 m, the transparency in the 500 nm to 1000 nm wavelength range
~~[drop]~~ drops off sharply.

15 Therefore, the ideal range for CO detection over a normal
range of RH is between 15nm to 30 nm for use with visible and near
IR wavelength photon emitters and detectors. A patent by R. Shoup
discloses a method to make pore structure of the appropriate size
using potassium silicate and colloidal silica. This method can be
20 used by itself or ~~combine~~ combined with the other method mentioned
above.

25 Once ~~[One]~~ the coating is in place, any number of coatings can
be added to the porous silica to sense a target gas. The sensitivity
depends on the evanescent wave, which is outside the core fiber and
enters the porous clad sensor.

Paul et al 1987 showed that the evanescent power of an
evanescent field absorption (EFA) fiber optic sensor has a well
defined electric field distribution outside the fiber waveguide,
which decays exponentially as it moves radially from the outer
30 surface. This evanescent field is typically 0.01 to 0.1 percent,
except in single mode fibers, which can be as high a 0.1 to 1.0 ~~[±]~~
percent or even higher.

The eigenvalues for the solution of the equation for a photon
in a waveguide can be employed to compute the normalized frequency
35 as follows:

1

$$V^2 = U^2 + W^2$$

Where ~~Where~~ U and W are eigenvalues for the core and cladding that
 5 arise from the solutions in an electric field in an optical fiber
 (Snyder 1974). For a porous sensor clad optical fiber, V may be
 defined as

10

$$V = 2\pi r l \lambda \{ \sqrt{[n(f)^2 - n(c)^2]} \}$$

~~Where~~ where r is the fiber radius, and n(f) and (c) are the indices
 of refraction of the fiber and porous cladding, respectively. Thus
 the equation demonstrates that for small values of V, i.e., small
 diameter sensors and for porous coatings with different indices of
 15 refraction from the fiber, there will be an evanescent absorption in
 the sensing media when it is exposed to the target gas, assuming the
 appropriate wavelength photons are employed. Therefore, ~~Micro-~~
~~optical-electronic machine systems~~ Micro-Optical Electronic Machine
Systems (MOEMS) are an excellent way to manufacture these sensors.
 20 The method involves the use of photolithography, etching, coating,
 etc., as described in "Silicon Micromechanics: Sensors and Actuators
 on a Chip" by Roger Howe et al IEEE Spectrum, July 1990; "Mirrors on
 a Chip" by Jack Moore, IEEE Spectrum, Nov. 1993; V. Kieman, Laser
 Focus World March 1997 pp 63-64; and Steven Ohr, Electronic
 25 Engineering Times, Aug. 4, 1997 ~~p-1-146~~ pp. 1-146, as well as DAPRA
 DOD Website under MTO, MEMS and MOEMS.

 The changes in photon intensity dI at the end of the fiber is
 proportional to the length I of the sensing region, the evanescent
 30 field absorption, i.e., proportional to the radius of the fiber, the
 fibers optical and physical properties and the sensitivity of the
 sensing layer S as well as the concentration of the target gas such
 as (CO). Thus the concentration of the (CO) can be monitored by
 measuring the rate of change of the evanescent absorption with
 35 respect to time t.

$$d(\text{evanescent absorption})/dt = k(\text{CO})$$

~~for~~ For other gases, the k may be different and for some sensing media, the equation may vary depending on material properties.

In some cases, such as CO, k is a constant. In general, K may be some function that needs to be determined experimentally. In the CO case, the concentration of CO is proportional to the change in the photon intensity of the specific wavelength over a dt interval. This is true in the initial response; however, the nature of one such CO sensor coating has been ~~show~~ shown to be proportional to both I and dt/dt .

Under certain condition, the derivative of the transmitted photons with respect to a time interval plus the actual transmitted photon intensity is proportional to the carbon monoxide (CO) concentration,

$$[\text{CO}] = k_1 \{dI/dt\} + I(K_2) \text{ at other times}$$

$$[\text{CO}] = k_2 \{ \text{I}(\text{n}) \}$$

when ~~[when]~~ dI/dt is very near zero

[and] And, when dl/dt is not linear such that the second derivative is not very near zero, than the sum of the two, i.e., $I(n)$ and dI/dt is divided by 2 or is [an] averaged or a mean[~~, in~~]. In addition, a weighted average is feasible such as represented by the general equation:

$$[\text{CO}] = c \{ k_1 \left[\frac{dI}{dt} \right] + k_2 [I(n)] \}$$

The approximation can be employed easily and can limit the cost of detector and has the capability of digital display.

Other approximations are also possible, e.g., the sum of averages or weighted averages over a series of registers

$$[\text{CO}] = k_1 (\text{dI}/\text{dt}) + K_2 [\text{I}(\text{n})]$$

1 This method may be useful in producing digital displaced CO concentrations.

The fiber optic system has limitation in size; however, optical waveguides can be miniaturized using Micro Optical Electro
5 ~~Optical~~ Machining ~~(MEOMS)~~ (MOEMS). The optical system may be useful for a variety of applications from sensing to controlling aircraft.

Example 3 illustrates the use of index refraction change to direct the photons. If ~~we use~~ the sensor is used as an optical switch, then ~~photon~~ photons in one waveguide may be directed to a
10 second waveguide. There may be a photon emitter that places photons (of a specific wavelength range) within waveguide 1. Assuming there is no reaction from the target gas, then these ~~photon~~ photons stay in waveguide 1; however, if the target gas exceeds a predetermined level, the index of refraction changes such that the photons are
15 directed to the waveguide 2.

Example 4 illustrates the use of a system that passes photons through the sensing area more than once. This method is referred to a multi-pass because the photons are ~~based though~~ passed through the active area many times. The method is well known in spectroscopy for
20 detecting gases. In this case, we are using the thin layer of a porous solid and amplifying the absorption by using reflectors or some other means to direct the photons through the thin reacted sensor media more than once. The more time the greater the absorption and thus the greater the change in the signal.

25 ~~SUMMARY OF THE INVENTION~~

____ One of the key advantages of the above examples is ~~there~~ increase the increased speed of response over conventional system described earlier. The fast sensors such as CO devices may be
30 incorporated into ~~vehicle~~ vehicles, which can respond to CO or other gases in a number of ways to protect occupants, control fuel cell reformers, and control air quality. The technology may be generally applied to the detection of chemical warfare (CW) agents as well as other gases. For example, hazards such as hydrogen, hydrocarbons,
35 CO, ammonia and various toxic pollutants may be monitored in near

1 real time with very short delay of the order of millisecond. In
addition, some of these methods can be miniaturized with low cost.

There [~~is~~] are provided several preferred embodiments of the
present invention. These embodiments include both apparatus and
5 methods for determining the concentration of various target gases at
very fast speed for which ~~example~~ examples were given above.

1. Miniaturize conventional absorption: Small ~~sensor~~ sensors are
as limited by diffusion rate.

2. Thin layer multi-pass: [~~this~~] This invention [~~use~~] uses photons
that pass through the sensor many times, either using a multi-
pass through the porous sensor.

3. EFA: Sensor ~~sensor~~ comprises a waveguide coated with a porous
sensing media.

4. Index of refraction changes: One such method uses the sensor to
switch photons from one [~~are~~] area to another.

 The present invention relates to a sensing system, which
comprises one or more optical responding sensors, which comprise a
coating onto porous transparent substrate. This field of invention
relates to a sensor and a sensing apparatus incorporating at least
one photon emitter such as an LED or laser diode and a photodetector
such as a photodiode. Standard photon multiplexing techniques used
in the telecommunication optical fiber industry are useful for
identifying some agents; others [~~other~~] require [~~very~~] multiple
photon emitter. These preferred embodiments use very little power
and have long life.

These multi-pass and EFA sensors are fail safe. These sensors
operate over the range from minus 40 C to +70 C. The technologies
are Solid State and use either infrared or visible or both.

Coiling an optical fiber makes one embodiment of an evanescent
wave sensor. One preferred embodiment of the EFA method is for

1 sensing CO. The EFA sensing system consists of at least two
separate materials: one, an optical waveguide and the other, a
porous coating which incorporates a material that changes [~~it~~] its
optical properties when exposed to one or more target gases, and a
5 [~~A~~] means to pass one or more wavelength photons through the fiber
such that one or more photon ~~wavelength~~ wavelengths are absorbed due
evanescent coupling. The specific pattern recognition from the
differences in absorption of various wavelengths yields a spectral
signature that is capable of rapid and specific identification of
10 most compounds of interest. For many simple ~~compound~~ compounds, only
one or two ~~wavelength~~ wavelengths may be needed. In addition, the
use of multiple wavelength can identify several compounds at one
time. The porous layer is made very thin, about 100 nm to 200 nm
(1000 to 2000 angstroms). It is then coated with a sensing medal
15 that changes its optical properties when exposed to CO. The coating
may be applied directly. By [~~by~~]-measuring the evanescent
absorption changes as a function of time and/or the absolute light
intensity value, the concentration of CO and other gases may be
determined.

20 For applications in controlling fuel cell reformers, two
sensors may be required. In a reformat stream comprising hydrogen
and very little oxygen, two ~~sensor~~ sensors may be used, one in the
reformat stream and the other in clean air. [~~By~~] When monitoring
the optical response I (nl) of the sensor (S1) at a time t, this [~~-~~
25 This] optical response is proportional to the CO concentration
within the one chamber. The other chamber has a similar design and
therefore will also have a similar sensor, which will be
regenerating [~~will~~] while the other is responding.

This EFA embodiment relates to an evanescent field absorption
30 sensor with a waveguide and an adjacent sensing media EFA-SM to
accurately detect CO over a wide range such as 5 to 1000 or even 10
to 15000 ppm over a short time, such as 1000 milliseconds. This
basic EFA-SM concept may be used to detect hazardous gases, such as
CO. These devices may be incorporated in or attached to various
35 vehicles and may be portable units such that it can be easily

1 carried for applications in locations other than the vehicles or
from one vehicle to the other. This invention includes applications
comprising gas detector systems, such as a carbon monoxide (CO)
sensor to very rapidly detect the presence of CO for reformer
5 controls. In addition, a signaling means may be incorporated to
alert the people of fire, CO hazard or other gaseous materials.
Optionally, the novel device can display digital information on the
target gas, e.g. concentration, compute and/or display the Time
Weighted Average (TWA), peak concentration over some predetermined
10 time interval, total dose from target gas exposure, concentration,
etc., and then display the information on the vehicle dash or other
location.

The EFA can be ~~[the]~~ computed by subtracting the background
loss.

15 The K series sensors ~~contains~~ contain a much higher
concentration of copper ions than a biomimetic composition disclosed
in US Patent 5,063,164, herein incorporated by reference. The
concentration of copper is more than 1000 times that of the
photometric (color) change sensors. This is because these sensors
20 are responding to IR absorption in the near IR below the threshold.

The reference sensor response to humidity is nearly identical to
the humidity response of CO sensor. The threshold of the high
copper CO sensors may be 200 ppm or 20,000 ppm.

25 BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be better understood with reference to the
following detailed description and accompanying drawings wherein:

Figures 1 and 1a are a miniaturized CO sensor using surface
mount LED and Photodiode (PD) and prism to direct the photon ~~though~~
30 through the sensor and then to the PD.

Figure 2 is a typical thin coating sensor that utilizes a
multi-pass photon arrangement.

Figure 3 illustrates an evanescent sensing device to measure
the optical change on a very small surface at a depth d, which was
35 coated on a waveguide.

1 Figure 4 illustrates an EFA sensing device with a straight waveguide with a coating that interacts with a target gas.

 Figure 5 illustrates an EFA sensor that comprises a coiled optical fiber core with a porous coating that reacts to the target gas.

5 Figure 6 illustrates an ~~EFA-ring~~ EFA-ring sensing device that provides a time measurement of the

 signal decay from the ring back to the waveguide.

 Figures 7a and 7b illustrate [a] switchable electro-optical ~~device~~ devices, which move the photons from the
10 straight waveguide to the ring EFA sensor, which absorbs photon proportional to the concentration of target gas, and then [~~Then~~]
 switch the photons back to the waveguide where they are [~~it is~~] measured.

 Figure 8 illustrates the use of a gas sensor used to switch
15 the photons from one waveguide to another by means of an index of refraction change. The photons move through the sensing element to the parallel waveguide on the opposite side of the sensor.

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1 DETAILED DESCRIPTION OF THE FIGURES

~~Figure 1 illustrates~~ Figures 1 and 1a illustrate a miniature surface mount LED ~~[150]~~ 140 and photodiode ~~[140]~~ 150 in an optical sensing system 100. The prism 110 directs ~~[the]~~ photons ~~[11-]~~ 115 to
5 ~~[the]~~ a sensor 145. The photons 115 from the LED ~~[150]~~ 140 pass ~~though the~~ through a target gas, which ~~reacts~~ react with ~~[a]~~ the target gas or vapor. There are two basic optical techniques that are incorporated as embodiments of this fast optical monitoring method, i.e., 1) transmission and 2) reflection. The prism
10 waveguide [110] may be replaced with other waveguide shapes (not shown). In Figure 1, the ~~[The]~~ prism transmits and then reflects photons 115, which pass through ~~[a]~~ the miniaturized sensor 145 and then strike the photodiode ~~[140]~~ 150. In Figure 1a, prism surface 110b transmits the photons 115 which pass through the miniaturized
15 sensor 145 and are then reflected by prism surface 110a before striking the photodiode 150.

Figure 2 illustrates a multi-pass transmissive sensing apparatus 200. This sensing device 200 can be used for a variety of gases. For~~[, for]~~ purpose of an example, the use of CO as the
20 target gas will be described; however, it in no way is limiting the target gases of this method. Passing ~~[the]~~ photons 215 through ~~[the]~~ a sensor 245 many times as shown in Figure 2 ~~below~~ may enhance the transmission method if ~~[the]~~ reflectors 212 and 213 are very reflective such that the signal is preserved. Figure 2 ~~illustrate~~
25 illustrates a multi-pass photon device 200 that comprises ~~[a]~~ the sensor 245 that comprises a porous optical material, which is coated with a sensing agent (not shown) to form the sensor 245. The target gas is directed to a ~~[the]~~ sensing surface 248, which reacts with the surface layer 248 in time $t(1)$ to a depth $d(1)$. The photons 215
30 emitted from a ~~[the]~~ photon source 240, ~~which~~ are reflected back and forth ~~though~~ through the sensor 245 by the reflectors 212 and 213. The photons are absorbed in the portion of the coating that reacts with the gas in time t and the signal is read by monitoring a ~~[the]~~ photodetector 250. Ten reflections ~~though~~ through the sensing
35 material (245) may be provided in this embodiment.

1 Figure 3 illustrates an EFA sensing apparatus 300. In the
case where the target gas is CO, a ~~and the~~ porous sensor coated may
consist of a porous transparent material about 1000- 2000 angstrom
(100 to 200 nm) thick coated with about [±] 1 to 2 molecular layers
5 of a supramolecular chemistry, which is optically responsive
~~responding~~ to CO. The sensing material comprises a chemical reagent
comprising at least one of the following groups:

Group 1 Palladium salts selected from the group consisting of
palladium sulfate, chloride, and bromide.

10 Group 2 Heteropolymolybdates such as silicomolybdic acid,
ammonium molybdate, alkali metal molybdates.

Group 3 Copper salts of sulfate, chloride, bromide and
perchlorate.

15 Group 4 Alpha, [-] beta gamma or delta cyclodextrins and ~~there~~
their hydroymethy, ethyl and propyl derivatives.

Group 5 Soluble salts of alkaline and alkali chlorides and
bromides and mixture thereof;

20 Group 6 Organic solvent and/or co-solvent and trifluorinated
organic anion selected from the group including dimethyl sulfoxide
(DMSO), tetrahydrofuran (THF), dimethyl formamide (DMF),
trichloroacetic acid, trifluoroacetate, a soluble metal
trifluoroacetylacetonate selected from cation consisting of copper,
calcium, magnesium, sodium, potassium, lithium, or mixture thereof;
and

25 Group 7 Soluble inorganic acids such as hydrochloric acid,
sulfuric acid, sulfurous acid, nitric acid, and strong oxidizers
such as peroxide, or mixture thereof.

30 To form a ~~[the]~~ sensing layer 345, which is located just
outside a ~~[the]~~ waveguide 318, ~~comprising~~ comprises the process of
fabricating the EFA sensing device comprising the steps of coating
the waveguide with a porous silica layer between 20 nm and 200
nm, [-] and then coating the porous silica surface with a sensing
agent.

1 A method of producing the porous transparent layer which
~~provide~~ provides the sensing platform for a self-assembled
supramolecular sensing agent in an evanescent ~~[filed]~~ field
absorption ~~[θ]~~ (EFA) sensor, is made by starting with a silicon
5 alkoxide, ~~[+]~~ and further comprising the step of ~~reaction~~ reacting
the silicon alkoxide with ~~[a]~~ an organic material with carbons from
4 to 12, ~~[+]~~ and further involves the hydrolysis of the complex to
form an organo-silicon compound that is a stable compound and is
soluble in non-polar solvents, and further dissolving the solid
10 organo-silicon in the solvent and then coating the waveguide with
the solution and further drying the coating and then heating it to
drive off the solvent. The waveguide substrate such as silicon
dioxide substrate and the porous silica are next slowly heated to
500 to 900 C and then cooled slowly to room temperature. This
15 cooling may be accomplished simply by shutting off the oven and
leaving the oven to cool over night.

The size of the pores is important and must be keep at 10 to
30 nm, with the preferred embodiment at about 200 to 270 nm. The
preferred embodiment may be fabricated using the information
20 disclosed in US Patents as well as the method disclosed in the US
Patent Applications given above. In addition, the method may
comprise the steps of adding a pore forming agent to the solvent
containing the organo-silicon, ~~[+]~~ and then dip or spin coating the
waveguide, drying and heating to remove all solvent and to burn out
25 the pore forming agent that results in a 150 to 300 nm pore
structure.

The CO sensor generally regenerates in air if the air has no
or very small amount of CO. In the absence of CO, i.e., operating
in clean air, the sensor is in the normal state or condition
30 indicated by a transmission of light (photons in the wavelength band
of interest), which is indicated by a characteristic optical value
I(0) and a zero value. If a target gas such as CO is present, the
sensor equilibrium is shifted as the reagent undergoes changes in
its optical density, i.e. ~~[+]~~ the sensor begins to ~~CHANGE its~~
35 ~~Photon (OPTICAL)~~ change its photon (optical) interaction ~~PROPERTIES~~

1 properties on the surface. The gas interacts with the outer surface
fast, but is then limited by diffusion ~~though~~ through the small
pore. A typical monolith sensor darkens or lightens on its outer
surface closest to the source (gas) depending on the particular type
5 of CO sensor. After a time $t(0) + t(1)$, which depends upon the gas
(such as CO) concentration and the duration of exposure to CO, the
sensor has changed over a thickness $D(1)$. If it were practical to
measure the $D(1)$ absorption only by aligning ~~[the]~~ a photon emitter
340 with ~~[the]~~ a photodetector 350 as shown in Figure 3, then a
10 rapid measurement could be made. In practice, it is difficult to
make this measurement because of alignment issues, therefore a
multi-pass sensing system is very useful to provide a very fast and
accurate response.

Figure 4 illustrates a straight waveguide system 400 with
15 porous coatings 445 on at least two sides and a reflector 412 on the
side opposite a ~~[the]~~ photon entry side 451. An ~~[the]~~ LED 440 emits
photons 415 of a particular wavelength, e.g., 400 nm to 1100 nm.
The photons 415 enter a ~~[the]~~ waveguide 418 ~~though~~ through the
polished surface 451 with the beam of photons 415 entering
20 ~~perpendicular~~ perpendicularly to the surface. The photons exit
~~perpendicular to~~ perpendicularly onto a ~~[the]~~ photodiode 450 as
shown. The ~~coating~~ coatings 445 ~~senses~~ sense the target gas such as
CO with evanescent interaction ~~interact~~ in the outer cladding 445.
The invention employs the use of internally reflected photons to
25 monitor the gas exposure and concentration of the target gas in the
cladding (coating on a waveguide). This EFA device 400 is
illustrated in Figure 4, which illustrates a possible MEMS optical
waveguide 418.

Figure 5 ~~illustrate~~ illustrates a fiber optic coil used as an
30 evanescent ring system 500 for the detection of gases and vapors.
The EFA ring system 500 can also be configured to ~~operated~~ operate
using an optical ~~ring~~ coil 560 with sensing media (not shown) coated
onto at least a portion of the coil 560, which is located close to
an ~~[the]~~ optical fiber 555. The evanescent coupling using porous
35 coating on coiled fibers has been proposed earlier by Goldstein and

1 Holmquist and others as mentioned above. The novel aspect of these
gas sensors is that a porous transparent cladding is first prepared,
coated at 100 to 2000 angstroms and processed at high temperature
over 350 C. Then, a sensing material is applied using self-assembly
5 nano-technology with molecules that comprise a mixture. [+]

The step of coating the waveguide is to immerse the waveguide
in a chemical reagent comprising at least the following groups for a
period of time:

Group 1 Palladium salts selected from the group consisting of
10 palladium sulfate, chloride, bromide and mixture thereof;

Group 2 Heteropolymolybdates such as silicomolybdic acid,
ammonium molybdate, alkali metal molybdates;

Group 3 Copper salts of sulfate, chloride, bromide and
mixtures thereof; [-]

15 Group 4 Alpha, beta, gamma, and or delta cyclodextrins and
their derivatives and mixtures thereof; [-]

Group 5 Soluble salts of alkaline and alkali chlorides and
bromides and mixture thereof;

Group 6 Inorganic or organic acid and or salt of organic or
20 inorganic compound that dissolve in the mixture in the presence of
the acid(s); and

Group 7 Strong oxidizer such as nitric acid, hydrogen peroxide
or mixture thereof;

and further removing the waveguide and porous outer layer from
25 the solution and then ~~[dry]~~ drying the waveguide system slowly over
1 hour to 7 days to form the supramolecular sensing complex. Next,
the waveguide system is ~~and the are~~ heated to about 50 C to 80 C for
a period of time varying between a few hours and a few days
depending on the size of the oven the circulation of the oven and
30 the amount of sensor in the oven.

Figure 6 illustrates an EFA sensing devices 600 that can be
fabricated using MOEMS technology. This device contains an
evanescent coupling that can move ~~[the]~~ photons 615 from a a ~~[the]~~
waveguide 660 to a ~~[the]~~ ring 666 and back. While the photons are
35 traveling in the ring, the EFA takes place proportional to the

1 concentration of the target gas such as CO. ~~If the~~ A photon emitter
640 ~~pulsed~~ pulses an amount of photons, of which ~~[that]~~ a portion ~~of~~
~~are couple~~ is coupled into the ring 666 because of the close spacing
and the materials used. The photons move from the emitter 640 to the
5 waveguide 660, to the ring 666, and then a portion ~~of which are~~ is
coupled back to the straight waveguide 660 after each circumference
passage of the photons around the ring 666. Some of these photons
615 are absorbed by ~~[the]~~ sensing coating 645, which absorption is
proportional to the concentration of the target gas (not shown).

10 Fig. 6 shows the evanescent system 600 that is positioned such that
a portion of these photons is coupled in either direction. If ~~one~~
~~measure~~ the decay time of the signal measures similar to plasma
resonance, then a low cost fast responding sensing system is
accomplished.

15 Figure 7A and 7B illustrate the use of a means to switch
photons into a ring coated with sensing media 745. ~~The photons~~
Photons 715 are passed from ~~[the]~~ a waveguide 760 ~~though the~~ through
a switch 777a or 777b to ~~[the]~~ a ring 766. Then, the position of the
switch may be changed to allow the reduced photon signal to be
20 transferred back to the waveguide 760. The photons 715 go ~~round and~~
~~round~~ around and around the ring 766 and are evanescently ~~couple~~
coupled to the sensing material 745 proportional to the thickness of
the coating, the diameter of the ring, the material and the index of
refraction, as well as the gas concentration of the target gas. [+]

25 As ~~[the]~~ they go around the small ring 766, the photons spend a
portion of their time outside the ring waveguide in the sensing
cladding 745. If the target gas has reacted with the cladding media
745, then some of the photons will be EFA in that cladding
proportional to the concentration of the target gas (not shown).

30 The longer the photons spend time in the small ring 766, the more
that is absorbed. In a few microsecond or a few milliseconds, the
switch can be activated allowing a portion of the photons 715 to be
passed back to the straight waveguide 760 and a ~~[the]~~ photodiode 750
can be place at one or more end(s). The photon signal is then read
35 by the photodetector 750. The difference between the intensity of

1 photons measured at some interval of time $t(I)$ is a measure of the
target gas concentration in near real time, that is, less than 1
second and perhaps less than 1 millisecond depending on the
parameters discussed above, ~~and~~ the gas concentration and the
5 speed of the switch.

Several methods of forming transparent porous sensor
substrates are given below. The major steps in forming a uniform
porous coating, which are bonded to a waveguide, are given for
silicon dioxide but can be used for many other metal oxides. In
10 Examples 7-1 ~~though~~ through 7-3 have porous silica of controlled
pore sizes with the average pore diameter 200 to 270 nm as measure
by a Quantachrome BET Model XXX. It is preferred that the pore
diameter not vary more than plus or ~~mine~~ minus 15%. Figure 7
illustrates [4] four steps to manufacture a sensor for evanescent
15 field absorption.

Step 1: The ~~[the]~~ precursor is ~~prepare in~~ prepared. In
Example 7-1 and 7-2, the precursors are TEOS and TMOS, respectively.
In and in example 7-3, it is a silicon tetra 2-ethylhexanoic acid.
Other organo-silicon compounds are feasible and the few examples
20 given are not intended to limit the method.

Step 2: Involves ~~two involves~~ preparing the solution and
applying the coating by dip or spray.

Step 3: Age ~~[is to age]~~, dry and then heat to about 500 to
675C.

25 [-]Step 4: Impregnate ~~is to impregnate~~ or coat the porous
silica with a sensing material and process.

Example 7-1

Water is mixed with nitric acid to form a 0.01N acid. Next, 0.75
30 grams of polyacrylic acid (Aldrich 19205-5) mw 250,000 is blended
with 10 ml of 0.01N acid to obtain a clear solution. Add 10 ml of
TEOS; stir gently, then heat in a closed container to 60 C for 10
minutes. Next, dip a waveguide into the solution. The solution is
useful for about 1 hour.

1 After coating, dry the coated waveguide in air for 1 hour then wash with nano-pure water and ethanol. Then, dry at 60 C for 1 hour. The dried sample has a pore size of 25 nm. The thickness of the ~~coating~~ coating can be controlled by the time of immersion.

5 During the first few minutes of gelling, the coating is 50 to 75 nm thick. At ~~at~~ 10 to 30 minutes, the coatings are about 80 to 120 nm, and the ~~coating~~ coatings done after 30 minutes are larger than 120 nm.

10 Example 7-2

0.023 grams Polyvinyl pyrrolidone (Aldrich 85656-8 mw 40,000) is dissolved in 10 ml of nano-pure water. Add 5 ml of TMOS and stir gently. Heat the solution at 55 C in closed container for several minutes, then open and place one test fiber into the mixture for a few seconds and remove. Test the coating for smooth bonding, size and uniformity. As soon as the proper coating is obtained, dip coat as many waveguide as possible within ten minutes. Then age for 2 hours each of the dipped waveguides. Then wash 3 times with water and ethanol. The pore average size will be about 25 nm.

20 Example 7-3

One preferred embodiment uses 2-ethylhexanoic acid. The evaporation of the solvent such as cyclohexane forms the green ceramic, which after controlled firing forms a thin porous silica layer with average pore diameter of 20 to 25 nm (200 to 250 Angstroms).

25 The ratio of the 2-ethylhexanoic acid added to the total silicon alkoxide is preferably in the range between 1 to 1 to 2.7 to 1 on a molar basis. The green ceramic is heated slowly to about 500 C to 600 C. The heating cycle can take from 12 to 24 hours depending on the amount of materials use in the furnace and the thickness of the coating.

30 Example 7-4

Any examples above are feasible; however, for clarity, the preferred manufacturing method is ~~show~~ shown. A coating solution

1 preparation: approximate 50 grams of above silicon tetra 2-
ethylhexanoic acid is added to 250 grams of cyclohexane to form a
clear liquid. The liquid is sprayed through a standard air/liquid
5 spray gun onto an unclad optical fiber. It instantly forms an
adherent coating under standard lab conditions. The fiber is then
heated to 550C in 12 hours and then allowed to cool to room
temperature. The oven is opened and the coated fiber removed. The
fiber is then placed in a humidity chamber for 24 hours, after which
10 it is placed in a solution containing the supramolecular complex
described in US ~~patents~~ Patent Nos. 5,063,164 and ~~US Patent No.~~
5,618,493. It is feasible to machine thousands of these devices in a
single chip using MEMS technology as referenced above.

Figure 8 illustrates [~~the~~] an index sensing switch system 800
comprising a photon ~~sources~~ source such as an LED 840 and a
15 waveguide 860 to receive photons 815 from the photon source, a
portion of which ~~are capture~~ is captured by the acceptance angle and
[~~stay~~] stays in the waveguide (WG1) 860 by total internal
reflection. The WG1 860 is optically coupled to [~~the~~] sensor 845
and is also optically coupled to waveguide WG2 861, which is located
20 on the opposite side of the sensor from [~~WGL~~] the waveguide 860.
There is a photodiode 850 located at the far end of WG2 861. If the
photons 815 transfer from WG1 to WG2 by a change in the optical-
properties of the sensor 845, then the photodiode 850 will register
the change proportional to the amount of photons striking the
25 photodiode 850. If the gas such as CO (not shown) is what changes
the optical properties to cause the photons to switch from the
waveguide 860 to the waveguide 861, then the system can sense this
change very rapidly in the order of milliseconds. The smaller the
system is, the more quickly the sensor changes. Figure 8
30 illustrates the use of a sensing switch system 800 that uses the
change in index of refraction due to the reaction of sensor
chemistry with a target gas or vapor. As the index changes, the
photons move from one position to another position (not shown).

1

Example 8-1

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An example is of an index of refraction change to switch the photons from waveguide (WG) 1 to waveguide (WG) 2 through the sensor S (the sensor may be a K sensor for fuel cell applications).

10

One skilled in the art would appreciate an apparatus and method for tracking the response of optically responding sensors for a variety of target gases such as CO. Today, current low-cost digital CO products ~~can not~~ cannot operate reliably for years with common batteries, such as 1.5 volt AA, AAA or 9 volts or similar batteries. Such an apparatus and method would increase the desirability of a wide variety of products from home detectors to military monitors, medical products, breath diagnostics to industrial controls to automotive gas sensing products and fuel cell reformers. Many of the current digital CO products on the market ~~that~~ are battery operated. These CO digital detectors use ~~either~~ electrochemical cells for sensors~~[-they]~~. They are very expensive, require frequent calibration, and frequent replacement. Or, they ~~[or]~~ use Metal Oxide Semiconductor (MOS) sensors which take very large amounts of power and therefore ~~can not~~ cannot be operated for a reasonable time of years or even months on small batteries such as a 9 volt battery. Therefore, there is a need for a reliable, low-cost accurate digital CO detector.

20

25

Furthermore, there is a need for [a] small, fast responding detectors to detect chemicals that may be released in a battlefield or civilian environment by an adversary. The tiny sensor can be fabricated on a small ~~[chip]~~ chip only a few microns. Therefore, it can stand the g forces ~~[need]~~ needed to send these sensors into the battlefield ~~[be]~~ in small vehicles or shells. The novel invention provides all of these advantages and has additional advantages of operating over a larger range of humidity and temperature, responding faster and providing more accuracy and more stability than any other technology.

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One skilled in the art may appreciate a low powered gas (such as CO) sensing apparatus, which can also, measure and display gas

1 concentration by calculations from the response of EFA for a variety
of target gases.

Such an apparatus and method would increase the desirability
of a wide variety of products from home detectors to military,
5 medical products, breath diagnostics to industrial controls to
automotive gas sensing products. These target materials include NOx,
CO, Hydrogen, CO2 as well as chemical warfare agents and explosive
vapors and many other volatile molecules.

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